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E6095

NASA Technical Memorandum 103804

Self-Pressurization of a Flightweight Liquid Hydrogen Storage Tank Subjected to Low Heat Flux

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Prepared for the
1991 ASME/AIChE National Heat Transfer Conference
Minneapolis, Minnesota, July 28–31, 1991

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ABSTRACT

This paper presents results of an experimental investigation of self-pressurization and thermal stratification of a 4.89 m^3 liquid hydrogen (LH_2) storage tank subjected to low heat flux (0.35, 2.0, and 3.5 W/m^2) under normal gravity conditions. Tests were performed at fill levels of 83 to 84 percent (by volume). The LH_2 tank was representative of future spacecraft tankage, having a low mass-to-volume ratio and high performance multilayer thermal insulation. Results show that the pressure rise rate and thermal stratification increase with increasing heat flux. At the lowest heat flux, the pressure rise rate is comparable to the homogenous rate, while at the highest heat flux, the rate is more than three times the homogeneous rate. It was found that initial conditions have a significant impact on the initial pressure rise rate. The quasi-steady pressure rise rates are nearly independent of the initial condition after an initial transient period has passed.

INTRODUCTION

Space flight in the coming decades will involve storage, acquisition, and transfer of cryogenic liquids under long-duration, low-gravity conditions. Cryogenic fluids are of interest for chemical and nuclear propulsion, life support, and thermal control. For well-insulated systems, the space thermal environment can result in heat leak rates of the order of 0.1 to 1 W/m^2. These heat leaks, although low, result in the inevitable pressurization of closed cryogenic storage systems. Long-duration missions such as required for human exploration of Mars require elaborate thermal protection of cryogenic liquids to reduce vaporization losses. Proposed cryogenic storage systems for these long duration flights consist of lightweight tankage insulated with multilayer insulation and vapor-cooled shields. Pressure control when necessary will be achieved by fluid mixing and the use of an open-loop refrigeration concept known as the thermodynamic vent system. An ongoing research program in cryogenic fluid management to improve our understanding of thermodynamic behavior in cryogenic systems is being conducted by the NASA Lewis Research Center. The results reported herein are concerned with long-term storage of LH_2.

Self-pressurization experiments with LH_2 have been conducted by NASA Lewis for both normal- and low-g environments. Ground-based experiments for small diameter spherical tankage have been conducted by Adyelott (1967a) and Adyelott and Spuckler (1969) for heat fluxes on the order of 30 to 300 W/m^2. Adyelott (1967b) performed low-g experiments with similar tankage and heat flux during a series of sounding rocket flights. In this sequence of NASA Lewis experiments, the effects of acceleration level, tank size, heat flux distribution, heat flux level, and percent filling on pressurization rate were investigated. For small scale tanks at the above heat flux, the heat transfer mechanisms are boiling at the liquid-wall interface (since the wall superheat exceeds that required for boiling incipience) and turbulent convection in the liquid. For heat fluxes above 0.01 W/cm^2, nucleate boiling occurs in LH_2 systems as reported by Brentari and Smith (1965). At lower heat fluxes, boiling will not occur, except possibly at isolated hot spots associated with penetrations through the insulation system. The mode of heat transfer within the tank is complex and is the greatest factor that controls the pressure rise rate.

An experiment by Liebenburg and Eduskuty (1965) with a very large-scale LH_2 tank (208 m^3) subjected to a heat flux of 1.9 W/m^2 shows the development of a warm thermal layer above the remaining bulk liquid and an associated pressure rise rate of 3.6 kPa/hr, a rate more than 10 times that for the corresponding homogeneous (a well-mixed, isothermal) system. This increased rate of pressure rise is the result of thermal stratification of the liquid cryogen. The stratification pattern is very dependent on the source of liquid heating with wall heating generally contributing most to the formation of a stratified liquid in normal gravity, e.g., see Tatom, et al. (1964). The heated liquid near the walls is convected toward the liquid surface under the action of buoyancy force, forming a growing layer of stratified liquid that is at a higher temperature than the bulk. Since the tank pressure is directly related to the interface temperature, the pressure rise of a closed container of stratified fluid is greater than that occurring if the fluid were homogeneous. Typically, thermal stratification involves three distinct zones within the liquid region: a boundary layer along the heated walls, a warm mixing layer immediately below the liquid-vapor interface that grows with time, and a central bulk region. This arrangement readily lends itself to analysis for simple tank shapes such as upright cylindrical tanks with side heating, e.g., Moses and Gluck (1972).

The purposes of the experiments reported herein were to obtain self-pressurization and thermal stratification data for a test tank having the same characteristics as propellent tanks of future spacecraft. The range of heat fluxes covered in the experiments is the same as expected in full scale applications of future space missions.

EXPERIMENTAL APPARATUS

Tests were conducted at the NASA Lewis Research Center's K-Site Facility located at Plum Brook Station in Sandusky, Ohio. This facility has a 7.6 m diameter vacuum chamber enclosing a 4.0 m diameter cylindrical cryoshroud which in turn encloses the LH_2 test tank. The shroud may be cooled with liquid nitrogen (83 K) or heated above ambient with electrical resistance heating (294 to 350 K) to obtain the desired heat flux. Vacuum chamber pressures on the order of 7 x 10^{-3} to 10^{-4} Pa are obtainable. The test article is suspended by 12 fiberglass composite struts, as shown in Fig. 1, and all instrumentation lines and most flow lines are routed through a LH_2 cold guard to minimize conductive heat transfer to the test article.

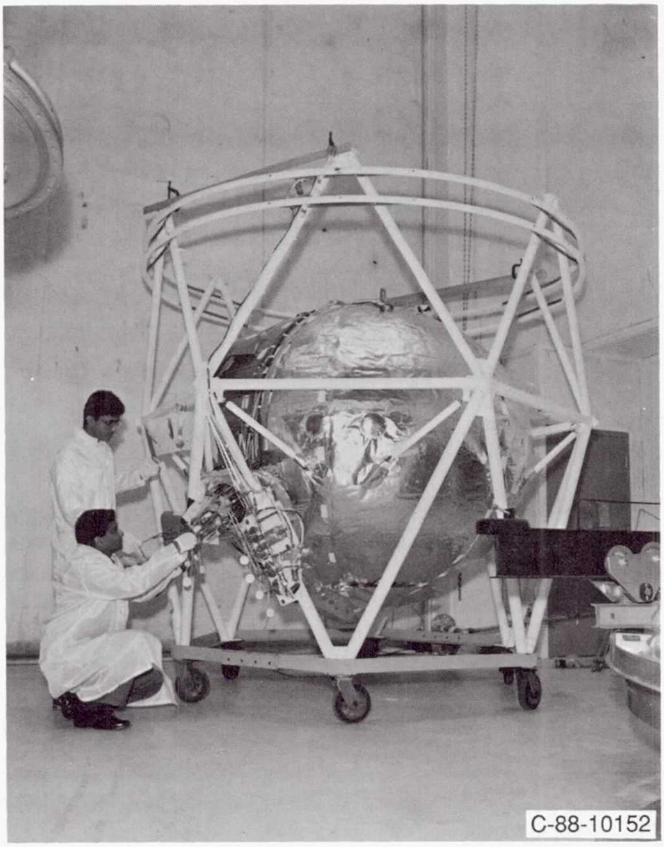

Figure 1.—Test article.

The LH_2 test tank is constructed of chemical-milled 2219 aluminum and insulated with 2 blankets of multilayer insulation, each having 17 layers of double aluminized Mylar separated by silk netting. It is approximately an ellipsoidal volume of revolution having a major-to-minor axis ratio of 1.2, a major diameter of 2.2 m, and a volume of 4.89 m^3. A 0.71 m diameter flange at the top provides access to the inside. The tank mass is 149 kg. Most of the wall is 2.08 mm thick except for the thick bolted flange and lid at the top, thickened lands for support lugs, and a thickened equatorial region. The tank insulation system, size, and lightweight construction (excepting the lid) is representative of the type of system that may be used in future orbital transfer vehicles.

Instrumentation of the test tank, shown schematically in Fig. 2, allows measurement of various parameters. Liquid fill level and liquid-vapor temperatures in the tank are measured by a capacitance probe and silicon diode transducers, respectively. The external wall temperature distribution is measured by a number of wall-mounted silicon diode transducers. Tank pressure is measured by pressure transducers located in the vent line. Figure 2 indicates the locations of the various sensors. Boil-off flow is measured by thermal dispersion type gas flow meters in the vent line. Liquid-vapor temperature measurements inside the tank are accurate to ±0.3 K, while wall temperatures are accurate to ±0.6 K. An in situ calibration increases the accuracy of liquid-vapor temperature measurements to ± 0.1 K by adjusting the individual sensor readings to known saturation conditions. Tank pressure measurements are accurate to ±0.01 kPa. Capacitance probe readings are accurate to ±1.9 cm, translating to a maximum error of ± 1.5 percent fill at the 50 percent fill level (by volume). Boil-off flow measurements are accurate to ± 0.030 and ± 0.089 standard m^3/hr (SCMH) for the 2.83 and 8.49 SCMH meters, respectively.

Analog data from instrumentation is sampled by an ESCORT-D data acquisition system. For self-pressurization and boil-off tests, the data is sampled at 1/2 hr intervals over the duration of the experiments. The data is transmitted to the NASA Lewis Research Analysis Center for storage and conversion to engineering units. Key data is available in real time at the test site.

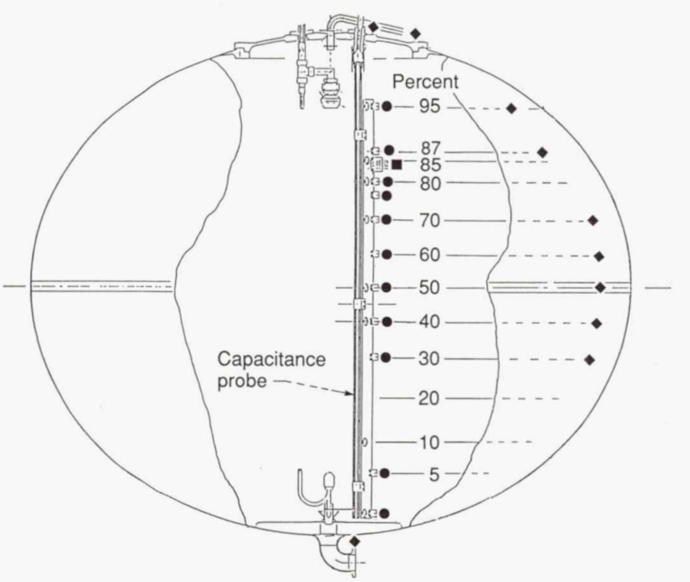

Figure 2.—Tank instrumentation.

TEST PROCEDURES

Boil-Off Test

Boil-off tests precede the self-pressurization tests for the purposes of conditioning the tank and insulation system and for determination of the total heat leak rate into the tank. The tank vent pressure is initially above the operating pressure of the backpressure control system and the tank is filled with LH_2 to 95 percent fill to cool the tank top section until wall-mounted sensors indicate temperatures within 0.5 K of the saturation temperature at the tank vent pressure. The vent pressure is then slowly decreased to the operating pressure of the backpressure control system (117 kPa for all tests). The boil-off rate is monitored until a steady state condition (less than 5 percent variation over 4 hr) is obtained for boil-off flowrate and fluid, wall, and insulation temperatures. After steady state, the tank is prepared for the first of the self-pressurization tests.

Self-Pressurization Tests

The tank vent valves are closed at the conclusion of the previous test (boil-off or self-pressurization) and the tank is slowly drained to a level slightly above the desired 85 percent fill level. Next, the tank pressure is reduced to the backpressure level (103 kPa) which induces substantial bulk boiling of the fluid that initially produces nearly isothermal conditions in the tank. Actual fill levels at the start of the tests ranged from 83 to 84 percent. The tests are performed using either of two initial conditions: an isothermal state or a steady boil-off state. If an isothermal starting condition is desired, the test is initiated by closing the vent line valves as soon as the tank lid temperature reaches its minimum value (typically 23 K). Otherwise, for a steady boil-off starting condition, tank venting is maintained until the liquid surface-to-tank lid temperature gradient and boil-off rate stabilize (a wait of 4 hr or more). After uniform boil-off and steady wall temperatures are obtained, the vent is closed to initiate the self-pressurization process. Tank pressure, and fluid and wall temperatures are recorded at regular intervals throughout the duration of the test.

TEST RESULTS

Boil-off Test

These results are reported elsewhere by Stochl and Knoll (1991); only a brief synopsis is provided herein. Separate boil-off tests were performed at the 95 percent fill level, with 83, 294, and 350 K cryoshroud temperatures. After a period of several days, the strut, insulation, wall, and fluid temperatures had approached steady state and boil-off was constant at rates of 0.45, 2.7, and 4.7 SCMH. Using these boil-off rates, the average heat fluxes were determined to be 0.35, 2.0, and 3.5 W/m^2, respectively. An example of boil-off flow rate and insulation temperature histories during a boil-off test is shown in Fig. 3. The data shown in Fig. 3 were obtained as the cyroshroud temperature was increased to 350 K, producing rapid transients followed by an approach to steady conditions. The dips in the inner insulation surface temperature correspond to unexplained conditions occuring during cold-guard refilling procedures.

Self-Pressurization Tests

Figure 4 shows the measured pressure rise as a function of time for each heat flux level. The data shown are for tests beginning with a steady boil-off condition. As one might expect, the pressure rise rate increases with increasing heat flux. It is noted that each test is characterized by an initial transient response followed by a period in which the pressure rise rate is nearly constant. The data at the high heat flux is most interesting, showing an initially rapid pressure rise rate from 0 to 2 hr, followed by a less rapid rise rate until approximately 6 hr. After 6 hr, the pressure rise rate increases and remains nearly constant for the remainder of the test.

The initial transient and steady pressure rise rates for the lowest heat flux (0.35 W/m^2) are more evident in Fig. 5, which spans the total test duration of 98.5 hr. A period of about 40 hr is required before the approximately constant pressure rise rate is attained. The pressure rise spike observed at the 52 hr mark is thought to be related to a cold-guard refilling operation performed at that time. After 70 hr, the steady

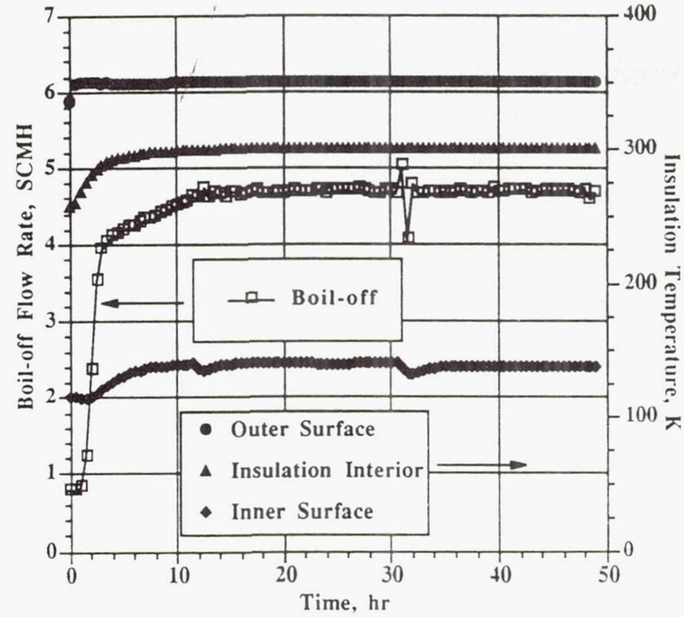

Figure 3.—Boil-off flow rate and tank insulation temperatures. Approach to steady heat flux = 3.5 W/m^2. Tank pressure = 117 kPa. Data from Stochl and Knoll (1991).

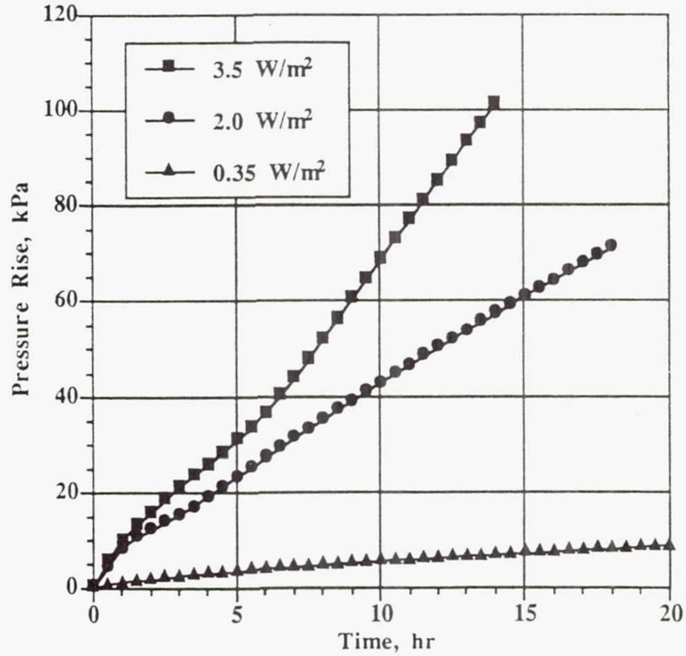

Figure 4.—Tank pressure rise as a function of average heat flux (steady boil-off initial condition).

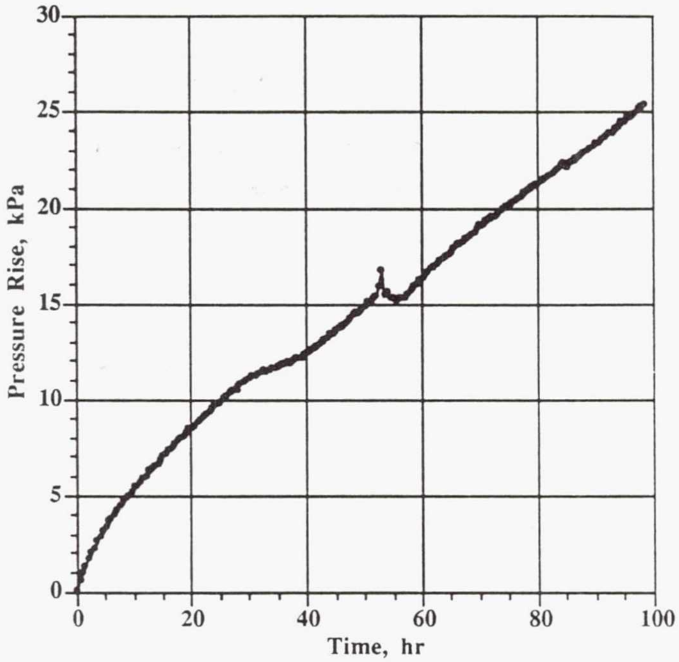

Figure 5.—Complete pressure rise history for heat flux of 0.35 W/m^2 (steady boil-off initial condition).

pressure rise rate is attained for a second time. A similar spike, much smaller in magnitude, occurred at 85 hr, during another cold-guard refilling operation.

Initial conditions were found to significantly affect the initial transient behavior of the tank pressure rise. Tests were performed using both the steady boil-off and isothermal initial conditions at heat fluxes of 2.0 and 3.5 W/m^2. Results of the higher heat flux tests are shown in Fig. 6. The data for the steady boil-off initial condition is the same as shown in Fig. 4. Data for the isothermal initial condition exhibits a quicker pressure rise rate during the initial portion of the test, followed by an approach to a pressure rise rate nearly the same as for the steady boil-off initial condition. For both initial conditions, the initial transient pressure rise rate is greater than the quasi-steady rate. The more rapid pressure rise rate at the beginning of the isothermal initial condition test is related to the tank lock-up procedure while the tank is venting vapor (boil-off) at a higher rate than during the start of a steady boil-off initial condition test. Because of the quicker pressure rise rate during the initial transient period in the isothermal i.c., this condition always results in a higher tank pressure than the steady boil-off i.c. Similar results were found for the test at a heat flux of 2.0 W/m^2.

Experimental pressure rise rates (after the initial transient period) are provided in Table I. Predictions of the pressure rise rate based on the homogeneous model are also included for comparison. The homogeneous model assumes a uniform temperature distribution in the fluid and in each case gives a slower pressure rise rate than the observed values. Since the homogeneous pressure rise rate increases with tank pressure, the values in Table I are averaged over the range of pressure rise corresponding to the individual tests at the various heat fluxes. It is apparent that as the heat flux increases, the measured(steady boil-off)-to-homogeneous pressure rise ratio increases. At the lowest heat flux, the ratio is close to unity, while at the highest heat flux it is more than three. As the heat flux is decreased, flow due to natural convection is reduced. Consequently, an increased fraction of the incoming energy is transferred to the bulk liquid instead of being convected to the liquid-vapor interface thus decreasing the rate of evaporation and pressure rise within the tank. Hence, the lesser degree of thermal stratification in the low heat flux condition results in a pressure rise rate which is closer to the homogenous prediction.

TABLE I. - COMPARISON OF MEASURED PRESSURE RISE RATES WITH HOMOGENEOUS THEORY

Heat flux, W/m^2	Pressure, kPa	Steady boil-off, kPa/hr	Isothermal, kPa/hr	Homogeneous, kPa/hr	Measured-to-homogeneous, ratio
0.35	121-128	0.223	-----	0.198	1.13
2.0	159-172	3.47	3.63	1.46	2.38
3.5	186-200	8.14	8.27	2.63	3.10

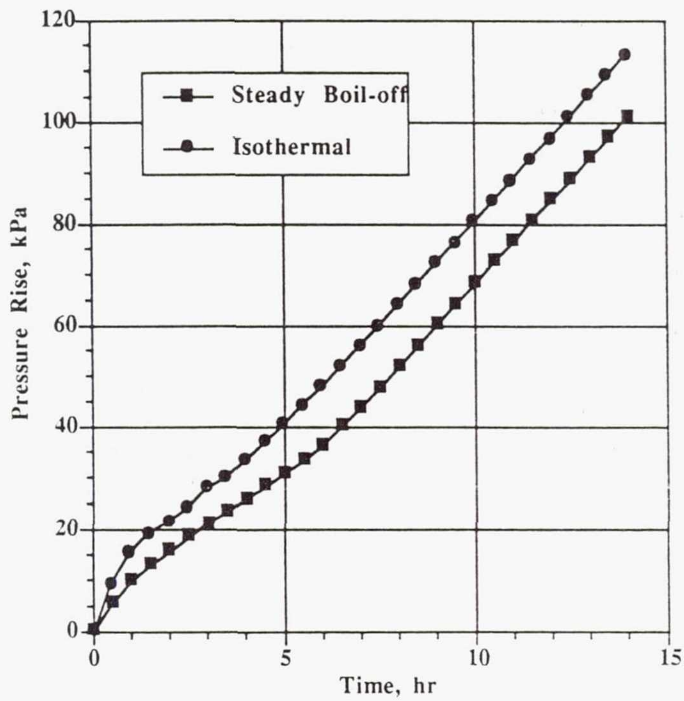

Figure 6.—Tank pressure rise comparison of two initial conditions at heat flux of 3.5 W/m^2.

The time variation of liquid and vapor region temperature distributions is shown in Figs. 7 and 8 for the steady boil-off and isothermal initial conditions at the 3.5 W/m^2 heat flux. Comparison of the temperature profiles at time=0 shows the differences of the initial ullage thermodynamic state for the two initial conditions. It is seen that the ullage region attains a quasi-steady state temperature distribution within a 4 hr period for both initial conditions. On the liquid-side, the liquid temperature continues to increase for the entire test duration. Close inspection of either figure reveals that the liquid surface (approximately 140 cm from the tank bottom at 83 to 84 percent fill) is at the saturation temperature corresponding to the tank pressure (obtained from Fig. 6). At the 12 hr mark, a warm layer underneath the liquid surface is evident (Figs. 7 and 8), having a depth on the order of 5 cm and thermal stratification (difference between saturation temperature and the bulk liquid temperature) of 1 to 2 K. The variation of liquid temperatures below a height of 127 cm is ±0.1 K, which is on the order of the measurement accuracy.

Temperature histories at selected locations in the liquid and vapor regions are provided in Fig. 9 for the high heat flux, steady boil-off i.c. test. Sensors above a height of about 140 cm are in the ullage region. It is seen that the vapor temperatures rapidly increase and then level off

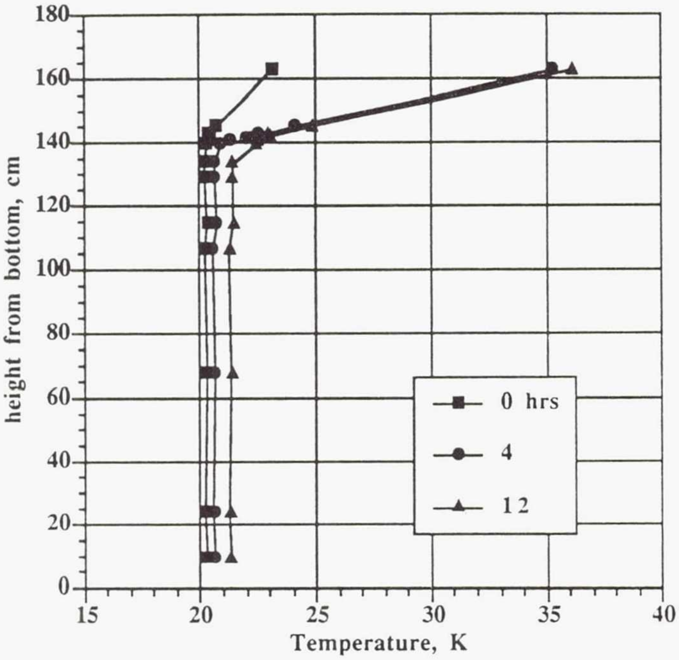

Figure 7.—Liquid-vapor temperature distributions for heat flux of 3.5 W/m^2 (steady boil-off initial condition).

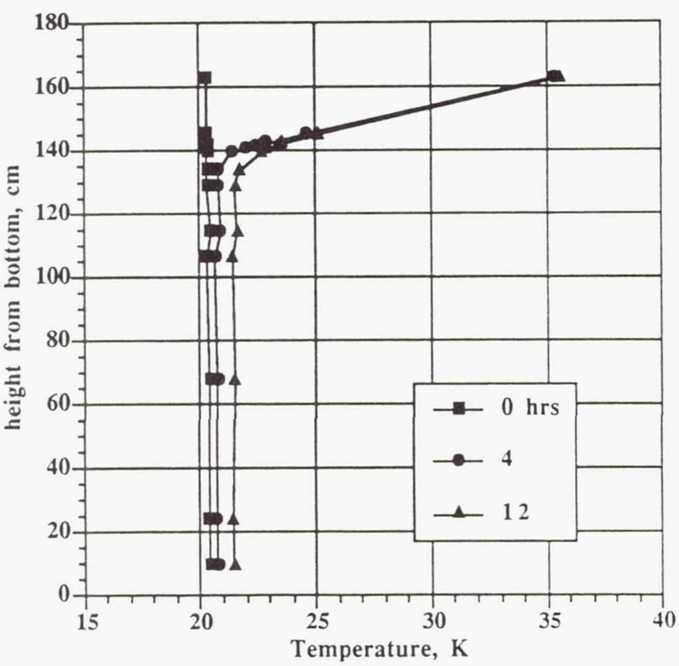

Figure 8.—Liquid-vapor temperature distributions for heat flux of 3.5 W/m^2 (Isothermal initial condition).

while the liquid temperatures increase in an approximately linear fashion. The sensor at a height of 139 cm was located very near the interface and its temperature history indicates that it was initially submerged and then exposed to vapor by the end of the test. The change of the temperature rise rates indicated in the figure at about 4 hr is due to the ullage attaining a quasi-steady state as discussed earlier in connection with Figs. 7 and 8, and also is thought to be related to the change seen at the 4 to 6 hr mark in Figs. 4 and 6.

Wall temperature histories are shown in Fig. 10 for the high heat flux, steady boil-off i.c. test. The tank lid is heated to 50 K within the 4 hr initial transient period and then remains near this temperature for the remainder of the test. The other wall locations appear to match the liquid and vapor temperatures measured near the vertical axis of the tank.

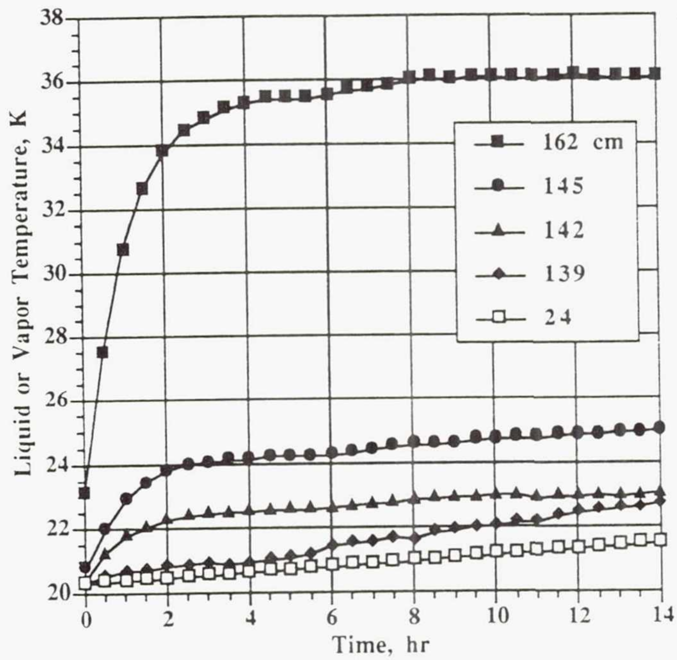

Figure 9.—Liquid-vapor temperature histories for heat flux of 3.5 W/m^2 (steady boil-off initial condition).

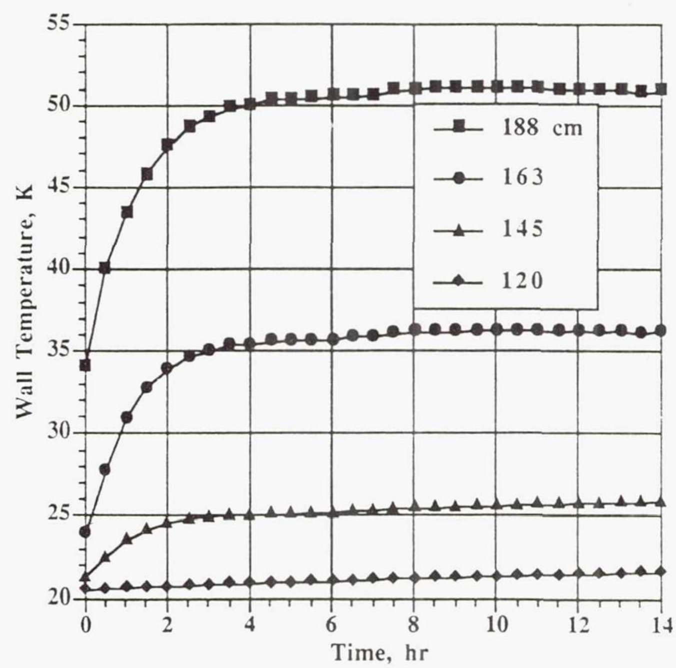

Figure 10.—Wall temperature histories for heat flux of 3.5 W/m^2 (steady boil-off initial condition).

CONCLUSIONS

Experimental measurements of self-pressurization rates have been obtained for a flightweight LH_2 tank having a high performance thermal protection system. Tests were conducted at fill levels of 83 to 84 percent in a 4.89 m^3 tank at heat flux levels from 0.35 to 3.5 W/m^2.

Results show that the pressure rise rate increases with increasing heat flux. At the lowest heat flux, the pressure rise rate was comparable to the homogenous pressure rise rate, while at the highest heat flux, the rate was more than three times the homogeneous rate.

It was found that initial conditions have a significant impact on the initial pressure rise rate. Lower rates were observed when the tank had previously experienced a steady boil-off rate due to a long period of venting, while a tank that is not at a steady venting condition will undergo a more rapid pressure rise after tank lock-up. The quasi-steady pressure rise rates are the same after an initial transient period has passed. In all tests, the initial pressure rise rate was found to significantly exceed the quasi-steady pressure rise rate; a phenomenon which should be considered when planning future pressure control experiments.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the teamwork of the many NASA Lewis employees and support service contractors involved with the K-Site Phase IB test program.

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NASA

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Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM - 103804		

4. Title and Subtitle
Self-Pressurization of a Flightweight Liquid Hydrogen Storage Tank Subjected to Low Heat Flux

5. Report Date

6. Performing Organization Code

7. Author(s)
M.M. Hasan, C.S. Lin, and N.T. Van Dresar

8. Performing Organization Report No.
E - 6095

10. Work Unit No.
506 - 48

9. Performing Organization Name and Address
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135 - 3191

11. Contract or Grant No.

13. Type of Report and Period Covered
Technical Memorandum

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546 - 0001

14. Sponsoring Agency Code

15. Supplementary Notes
Prepared for the 1991 ASME/AIChE National Heat Transfer Conference, Minneapolis, Minnesota, July 28-31, 1991. M.M. Hasan, NASA Lewis Research Center. C.S. Lin, Analex Corporation, 21775 Brookpark Road, Fairview Park, Ohio 44126 (work furnished by NASA Contract NAS3-25776). N.T. Van Dresar, Lewis Research Center. Responsible person, M.M. Hasan, (216) 433-8349.

16. Abstract
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17. Key Words (Suggested by Author(s))
Cryogenic fluid storage
Stratification
Fuel tank pressurization

18. Distribution Statement
Unclassified - Unlimited
Subject Categories 28, 34

19. Security Classif. (of the report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified	8	A02

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161